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Binaural Phase Difference as a Factor in Sound Localization

by Carl Richards Brown

1912

Submitted to the Department of Physics of the University of Kansas in partial fulfillment of the requirements for the Degree of Master of Arts

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A Thesis Submitted To The

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Th e object of the investigation herein to be reported was to test more throoughly and accuratel than heretofore, the theory that the binaural phase relation forms the basic factor in the localization of sounds of low pitch, especially those below one hundred and twenty-eight vibrations per second. It was not the purpose of the investigation to collect further evidence in favor of other more commonly recognized factors in sound localization, such as the binaural intensity ratio, or binaural timbre differences, for which there is already a large mass of indisputable evidence, but the work was closely confined to the one problem of finding evidence which would be reasonably sufficient for regarding the question of phase-difference function as settled on one side or other.of the question

The theory was first proposed in 1876 by Lord Rayleigh[1], in a paper in which he showed by mathematical anglysis of the case of incidence of plane sound waves upon a rigid spherical object, that the intensity between two points on opposite sides of this sphere is less than one per cent of the total intensity, for pitches of 128 vibrations per second and lower. This slight diffenence of intensity he thought to be insufficient to determine localization, and yet he found that sounds of that low pitch were localized as well as others of higher pitch.The possibility that sounds of such low pitch might be localized by binaural selection and intensity relation of overtones will be considered later.

The slight difference in intensity of a sound of 128 vibrations per second or less at the two ears is due to the absence of the "shadow" effect where the wave length is several times the thickness of the object in the path of the wave. When the wave-length is less than, or only slightly greater than the thickness of the obstacle, then the "shadow" effect is considerable. This phenomenon is very clearly illustrated by the analogous case of waves on the surface of water passing around a stationary object in the water. If waves whose crests are separated by several feet pass by a small pole a few inches in diameter, there is at no time a noticeable difference in the height of the water on opposite sides of the pole. If however small waves or ripples only a few inches apart pass around a large piling a foot or two in diameter, there will be a noticeable smooth strip of water beyond the piling. The first case parallels the effect of the head upon sounds of low pitch, and the second the effect of the head upon sounds of high pitch.

Lord Rayleigh's first experiment in support of his th theory was that of sounding two slightly mistuned tuning forks, one opposite each ear. Thus, in a period of time depending upon the pitch of the forks used, the phase relations of the two sounds pass through all values from 0° to 360°. The result of this experiment was a periodic oscillation of the body of the sound from one side of the median plane to the other, and by conducting the sounds of these forks to another observer and allowing them to combine to form beats, Rayleigh was able to show, from the nature of the agreement between the signals given by the one observer when the sound was localized on the right, and those given by the other observer when the beats occurred that the leading wave carried with it the localization.

At about the same time Thompson[2] inserted the ends of a curved copper wire into the ears of an observer, and held the stem of a vibrating tuning fork on the wire at various points. When the stem of the fork rested on the middle point of the wire, the sound "seemed to come from the ends of the wire into the ears." When the fork was displaced to the right or left from the middle, the report is that the sound no longer seemed to come from the ends of the wire, but from the back of the head. Although right and left effects are not specifically reported, it is probable that such effects were present to some extent, but were overlooked on account of the more noticeable effect of shifting to the back.

Later Lord Rayleigh [3] described a method of testing his theory, in which two telephone were separately excited by a rotating magnet which acted upon two stationary coils, one in each telephone circuit, one coil being adjustable in position with respect to the other so that any phase relationship between the sounds could be maintained constantly as long as desired. This method had the advantage of making the intensities of the two sounds adjustable to perfect equality for all phase relations. There is a grave probability, however, that the sounds thus produced were of a very complex and complicated character, so that in addition to a certain phase relation for the fundamental there were probably several others sets of phase relations of unknown character, corresponding to the different overtones. However, Rayleigh got results entirely consistent with his theory.

The next investigation of the subject was carried out in 1907 by More and Fry,[4] working with pitches of 320 and 512 vibrations per second. They used two heavy rubber tubes terminating in the subjects ears, at one end, and connectigg at the other end with a glass Y-tube which in turn connected with a glass funnel located about seven feet behind the observer. The sound was given before this funnel. The rubber tubes were cut in the middle to provide for the insertion of glass tubes of various lengths, so that the phase relation could be controlled. The sections of tube provided for insertion were long enough to provide for a maximum phase difference of about 7/8 of a period, a detail which is of importance in the comparison of these results with those obtained by Wilson and Myers[5], and which will be discussed later. The results obtained in this experiment are consistent with Rayleigh's theory bu do not require it as explanation.

The sound was always localized on the side of the shortest tube, which was a condition of leading wave whenever the inserted tube was less that half the wave length of the sound, as well as a condition of greater intensity due to the relative shortness of the tube. The results are thus practically valueless as evidence in suppr?ot of the phase theory. The fact that the localization did not follow the leading wave always may be accounted for as due to the very great damping of the sound when the leading wave was traveling through the greater length of tubing, as must have been the case on account of the small size of tubing used (about 1 cm. in diameter). Furthermore, the pitches used, viz., 320 and 512 vibrations per second are both very much above the limit of 128 vibrations set by Rayleigh.

We come now to probably the most important and most carefully conducted investigation of the problem, viz., that by Wilson and Myers[5]. The apparatus which they used consisted of a rectangle, approximately 317 by 150 centimeters, of glass and brass tubing about 2 cm. in diameter, in the middle of one of the long sides of which a short section corresponding to the thickness of the head was removed and caps fitted to the ends to cover the ears. In the opposite side a closely fitting sliding section with a hole in the middle with funnel attached, was arranged so that the sliding of this funnel opening from one extreme position to the other would provide for a wide variation in the relative lengths of the two paths for the sound from the funnel shaped opening to the ears.. The distance through which the slide could be moved was several times half the wave length used. With this provision, supposing that the sound is always localized nearest the ear hearing the leading wave, there should be a cyclic oscillation of localization as the opening before which the tuning forke is held is moved from one extreme position to the other. For, a lead of $180^\circ + \theta$ at the left ear is of course a lead of θ at the right ear, so that we should expect the localization to shift from one side to the other as the phase relation becomes greater than 180°, or in the apparatus just described, as the opeing in the sliding tube is displaced more than one fourth the wave length from the center, and as the phase relation becomes greater than 360° (the corresponding position of the opening in the tube being one half the wave length displacement from the center) the sound should shift to its original position. For phase relations of 0°, 180°, 360°, 540°, etc.. we expect to get median localizations, the corresponding displacements of the opening in the sliding tube being 0, $L/4$,$L/2$. $\frac{3}{4}L$, etc., in either direction from the center, when L is the wave length of the sound.

If the subject sits so that his right is the operator's right, then he should get localizations on the right side of the median plane, for displacements of the opening in the sliding tube, to right of center between the pairs of values 0 and L/4, L/2 and $\frac{3}{4}$L, L and 5L/4, 3L/2 and 7L/4, etc., and to the left between the values $\frac{1}{4}$L and $\frac{1}{2}$L, $\frac{3}{4}$L and L, 5L/4 and 3L/2, etc., and localization on the left for all other positions of the opening. With certain exceptions and variations that may be explained as due to resonance of tubes, impurities of tones, difference in sensitivity of the ears of the subject, etc., these are exactly the results that Wilson and Myers obtained.

The criticism of the work of More and Fry, viz., that their results may be explained on an intensity difference basis, due to shortening of one tube, is not applicable to the results of Wilson and Myers, because they used differences in length of pathways of sound of several times the wave length, and still obtained cyclic oscillation in localization, as stated above. For example, when the opening in the sliding tube is displaced from the center some distance which is greater than $\frac{3}{4}$L and less than L, the sound is localized on the side of the head to which it passes through the longer of the two sections of tubing, though it is slightly the weaker sound on that account. The conditions are such, however, that the wave on this side leads, and it determines the localization. The evidence is therefore conclusive that binaural phase relation operates in some manner to influence localization.

Ferree and Collins(6) attempt to discredit the work of More and Fry, and Wilson and Myers, by claiming the existence of a discrepancy in their results. They point out

That Wilson and Myers obtained periodic oscillations of localization, and that More anf Fry did not though working by practically the same method.[2] That there is no discrepancy whatever is evident from the two following considerations: (1) That More and Fry used a difference in lengths of the two branches of tubing never greater than 7/8 of a wave-length, and therefore giving only one possible shift in localization, whereas Wilson and Myers used differences in lengths of tubing several times the wave lengths, therefore getting many oscillations of localization, and (2) that the one possible shift of localization in More and Fry's method was probably lost on account of the small size of the tube which they used, which must have caused much more damping of the sound than was present in Wilson and Myers' experiment. The tube that More and Fry used was about one-half the diameter and consequently only one fourth the cross sectional area of that used by Wilson and Myers.

Wilson and Myers, though forced by the results of their experiment to recognize the binaural phase relation as a factor in localization, attempt to show that it acts only as an indirect method of producing an ultimate intensity difference at the ears, so that the localization after all is on an intensity ratio basis. The assumption, which will be questioned later in this paper, is made that by bone conduction in the head a certain percentage of the original sound affecting one ear is carried through the head to the other ear, so that the total effect at one ear is the resultant, the principal wave coming to it through the air, and one much diminished in intensity,—— and differing in phase by an angle due to the original phase difference at the two ears, and the further change in phase due to the thickness of the head,——which comes through the head from the other ear. Wilson and Myers attempt to prove that these transmitted waves interfere with the original waves in such a manner as to produce a constant difference in intensity, with the resultant of greater intensity on the side of the head which receives the leading wave. Their attempt at geometrical proof of this proposition is somewhat as follows : They say: "Suppose the sound entering the right ear is of equal intensity to that entering the left ear, but let the phase of the vibration at the right ear be ahead of that at the left. This is represented in the figure (Fig. 1) where OA represents the amplitude at the right ear, and O'A' = O A that at the left ear, and the angle AON is greater than the angle A'O'N'." They then draw OD parallel to A'O' but in the opposite direction and shorter to represent the weaker wave transmitted from the left ear through the head, and O'D' parallel to AO but in the opposite direction, and equal to OD to represent the same condition at the left ear. Then they draw OC and O'C' equal to OD and O'D' so that the angles COD and C'O'D' are equal, and so that the angle O'OC is less than the angle O'OD, and the angleN NO'C' is less than the angle NO'D' (all angles being measured in the counter-clockwise direction). This latter condition is necessary in order to represent the slight retardation in phase which the transmitted wave suffers in traveling the interaural distance. The parallelograms ABCO and A'B'C'O' are then completed, and the diagonals drawn. Since the diagonal OB is greater than the diagonal O'B', Wilson and Myers argue that the ear that receives the leading wave also is affected by a sound of greater intensity than that affecting the other ear. The error of this discussion of the case lies in the fact that for a given direction of rotation of the vector representing one wave train affecting one ear we must have rotation in the opposite direction of the vector representing the other wave train affecting the same ear, since these wave trains move in opposite directions. The representation of the transmitted wave by a vector drawn in a direction opposite to that of the vector representing the original wave, is false since this assumes the effect of opposite directions of motion to be the same as the effect of 180° phase difference for motions in the same direction.

The necessity for rotation of the vectors in opposite directions may be made clear by the following discussion: Suppose the right and left ears to be located at the points R and L respectively (Fig. 2) and to be affected by waves

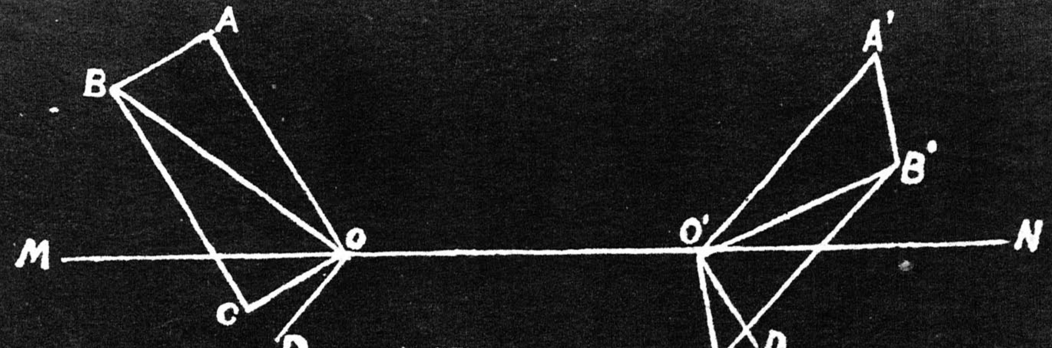


Fig. 1

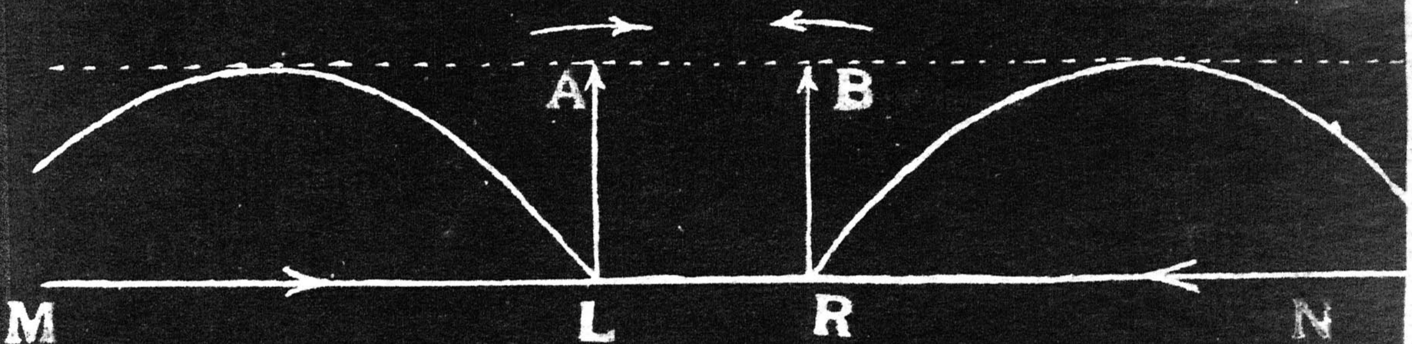


Fig. 2

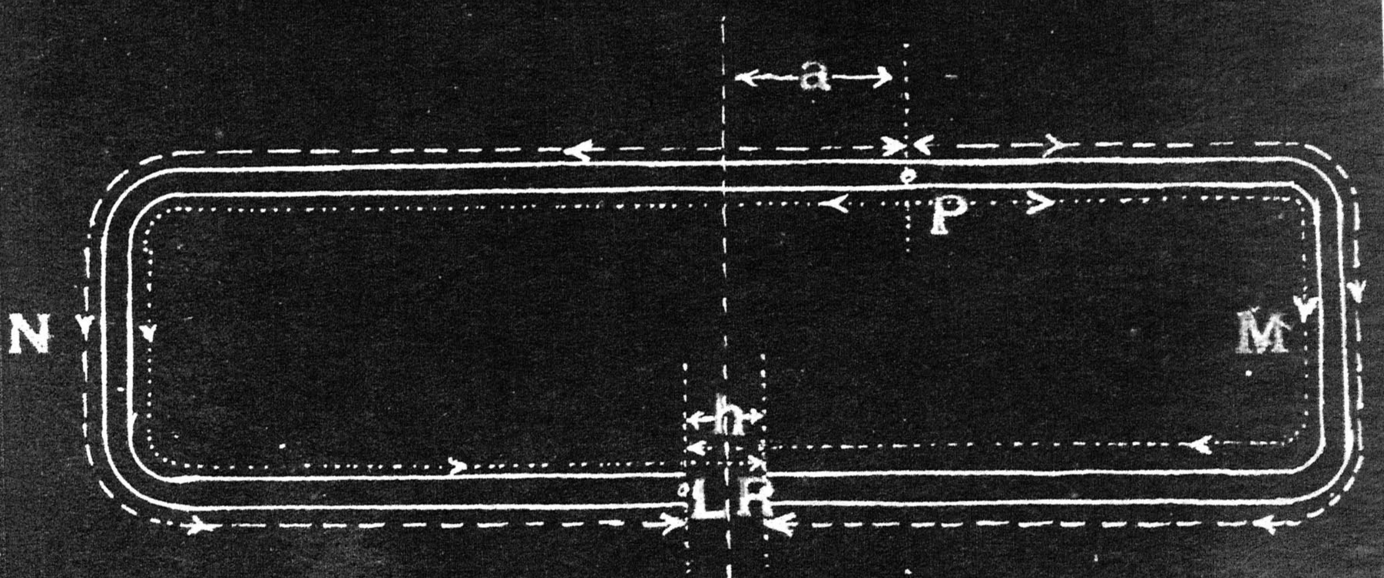


Fig. 3

of equal amplitude with zero phase difference. The projection of the vector BR upon the line MN represents the displacement of the particles of the medium, by the wave on the right and similarly the projection of the vector AL represents the displacement caused by the wave on the left. As the wave at the right travels toward the left there will be a displacement of particles toward the left, and consequently we must give the vector a rotation in the counter-clockwise direction in order to represent all the conditions. Similarly, as the wave at the left travels toward the right there will be a displacement of particles toward the right, necessitating the rotation of the vector AL in the clockwise direction. Since the vectors representing the direct and transmitted waves at each ear must rotate in opposite directions, and since the combination of forces by the graphical method can not be applied in such cases, the demonstration given by Wilson and Myers is fallacious and meaningless.

That the result of this assumed interference in the head is actually of exactly the opposite nature can be shown by proper combination of the equations of the wave-trains. Suppose the two ears to be located at the points L and R (Fig. 3) at the ends of the tubing of the rectangle such as used by Wilson and Myers. And suppose the sound to be given at some asymmetrically located point as P at a distance a to the right of the point equally distant from the two ears. Then the right ear will be affected by a wave traveling around the path PMR, and to a considerably less extent by a wave traveling around the path PNL and through the substance of the head. Similarly the left ear will be affected by waves travelling the paths PNL and PMRL equal in intensity toe the waves PMR and PNLR respectively. The equation of the wave affecting the right ear directly will be

$$y_r = \sin \frac{2\pi}{L} \cdot \frac{t}{T}$$

and that of the wave affecting the left ear directly will be

$$y_l = \sin \frac{2\pi}{L}\left(\frac{t}{T} + 2a\right)$$

where L is the wave length of the sound, t is the independent variable of the equation, and may be considered as time, and T is any initial time relation, which will be assumed unity throughout this discussion. The wave

$$y_r = \sin \frac{2\pi}{L}\frac{t}{T}$$

will pass through the head and affect the opposite ear with much diminished intensity which we will represent by the expression:

$$y_l' = k \sin \frac{2\pi}{L}\frac{t}{T}$$

It will require a sertain time interval t' for this wave to pass through the substance of the head, and we shall have to combine the transmitted wave with that condition of the direct wave which obtains later by the period t'. Thus, the total effect at the left ear is given by the expression:

$$Y_l = \sin \frac{2\pi}{L}\left(\frac{t + t'}{T} + 2a\right) - k \sin \frac{2\pi}{L}\frac{t}{T}$$

where 2a is the added distance that the sound must travel in order to affect the left ear directly, and where the minus sigh between the two members is used to account for the fact that the waves are traveling in opposite directions, a condition in which it is evident that displacements differing in phase by less than 180°, tend to neutralize each other, and displacements more than 180° apart tend to reinforce one another.

In a similar fashion we find the resultant of the waves affecting the right ear to be expressed by the equation:

$$Y_r = \sin\frac{2\pi}{L}\left(\frac{t+t'}{T}\right) - k\sin\frac{2\pi}{L}\left(\frac{t}{T}+2a\right)$$

That both of these resultants are pure sine waves differing in amplitude may be shown as follows:

Expanding the two equations given above we get:

$$\begin{aligned} Y_r = {} & \sin(2\pi t/LT)\cos(2\pi t'/LT) + \cos(2\pi t/LT)\sin(2\pi t'/LT) \\ & - k\sin(2\pi t/LT)\cos(4\pi a/L) - k\cos(2\pi t/LT)\sin(4\pi a/L) \end{aligned} \quad (1)$$

$$\begin{aligned} Y_r = {} & \sin(2\pi t/LT)\left\{\cos(2\pi t'/LT) - k\cos(4\pi a/L)\right\} \\ & + \cos(2\pi t/LT)\left\{\sin(2\pi t'/LT) - k\sin(4\pi a/L)\right\} \end{aligned} \quad (2)$$

$$\begin{aligned} Y_l = {} & \sin(2\pi t/LT)\cos(2\pi/L)(t'/T+2a) \\ & + \cos(2\pi t/LT)\sin\left\{\frac{2\pi}{L}(t'/T+2a)\right\} - k\sin(2\pi t/LT) \end{aligned} \quad (3)$$

$$\begin{aligned} Y_l = {} & \sin(2\pi t/LT)\left\{\cos\frac{2\pi}{L}(t'/T+2a) - k\right\} \\ & + \cos(2\pi t/LT)\sin\frac{2\pi}{L}(t'/T+2a) \end{aligned} \quad (4)$$

Multiplying and dividing the left hand side of equation (2) by $\sqrt{1+k^2-2k\cos(2\pi/L)(t'/T-2a)}$ we may then write:

$$Y_r = \sqrt{1+k^2-2k\cos(2\pi/L)(t'/T-2a)}\,.\sin(2\pi t/LT+p)$$

where

$$\cos p = \frac{\cos\frac{2\pi t'}{LT} - k\cos\frac{4\pi a}{L}}{\sqrt{1+k^2-2k\cdot\cos(2\pi/L)(t'/T-2a)}}$$

and

$$\sin p = \frac{\sin\frac{2\pi}{L}\frac{t'}{T} - k\sin\frac{4\pi a}{L}}{\sqrt{1+k^2 - 2k\cos\frac{2\pi}{L}(\frac{t'}{T} - 2a)}}$$

In a similar fashion we may reduse equation (4) to the form:

$$Y_1 = \sqrt{1+k^2 - 2k\cos\frac{2\pi}{L}(t'/T+2a)}\cdot\sin(\frac{2\pi t}{LT} + p')$$

where

$$\cos p' = \frac{\cos\frac{2\pi}{L}(t'/T + 2a) - k}{\sqrt{1+k^2 - 2k\cos\frac{2\pi}{L}(t'/T + 2a)}}$$

and

$$\sin p' = \frac{\sin\frac{2\pi}{L}(t'/T+2a)}{\sqrt{1+k^2 - 2k\cos\frac{2\pi}{L}(t'/T + 2a)}}$$

We therefore find that the right ear is affected by a pure sine wave (supposing the original sound to be a pure tone) of amplitude $\sqrt{1+k^2 - 2k\cos\frac{2\pi}{L}(t'/T - 2a)}$, and the left ear is affected by a pure sine wave of amplitude $\sqrt{1+k^2 - 2k\cos\frac{2\pi}{L}(t'/T + 2a)}$. It will be seen that these amplitudes depenf upon the phase relation $\frac{4\pi a}{L}$, upon the thickness of the head h (t' = h/v, v being the velocity of the sound in the head substance, possibly slightly greater than in air, but this is not of great importance since the problem is concerning relative and not absolute values) and upon the percentage of sound transmitted through the head, k. But most important of all is the fact that the amplitude affecting the right ear is less than that affecting the left ear when $\frac{4\pi a}{L}$ is less than 180°, and greater when the phase difference is greater than 180°. This is true since the cosine of the sum of two angles is less than the cosine of the difference. But when $\frac{4\pi a}{L}$ is less than 180° the wave affecting the right ear is leading, and when $\frac{4\pi a}{L}$ is greater than 180° the leading wave is at the left ear.

The effect of interference may be shown in the following manner also: Suppose two sound waves meet each other in a contincus tube cac' (Fig. 4) , in equal phase at a point a. If we consider the ordinates of the curves aM_1bm_1c and $aM_1'b'm_1'c'$ to represent the degrees of compression and rarefaction due to these waves separately, then the maxima of compression M_1 and M_1' will reach a at the same instant and produce a compression which will be slightly less than the sum of the compressions of the two waves, owing to the imperfect elasticity of the medium. Similarly the maxima of rarefaction m_1 and m_1' will reach the point a at the same instant, and produce a doubly intense rarefaction corresponding to he double compression an instant before. Thus we aill have a variation is pressure at the point a' represented by the distance Mn. In the figure one pair of points of normal pressure are are coincident at the point a. The point of normal pressure b will reach the point d_1' simultaneously with the point a of normal pressure. Likewise the point of maximum rarefaction m_1 will reach d_1 simultaneously with the maximum of compression M_1', thus exactly neutralizing it. Thus it develops that the result is a"standing" wave represented by

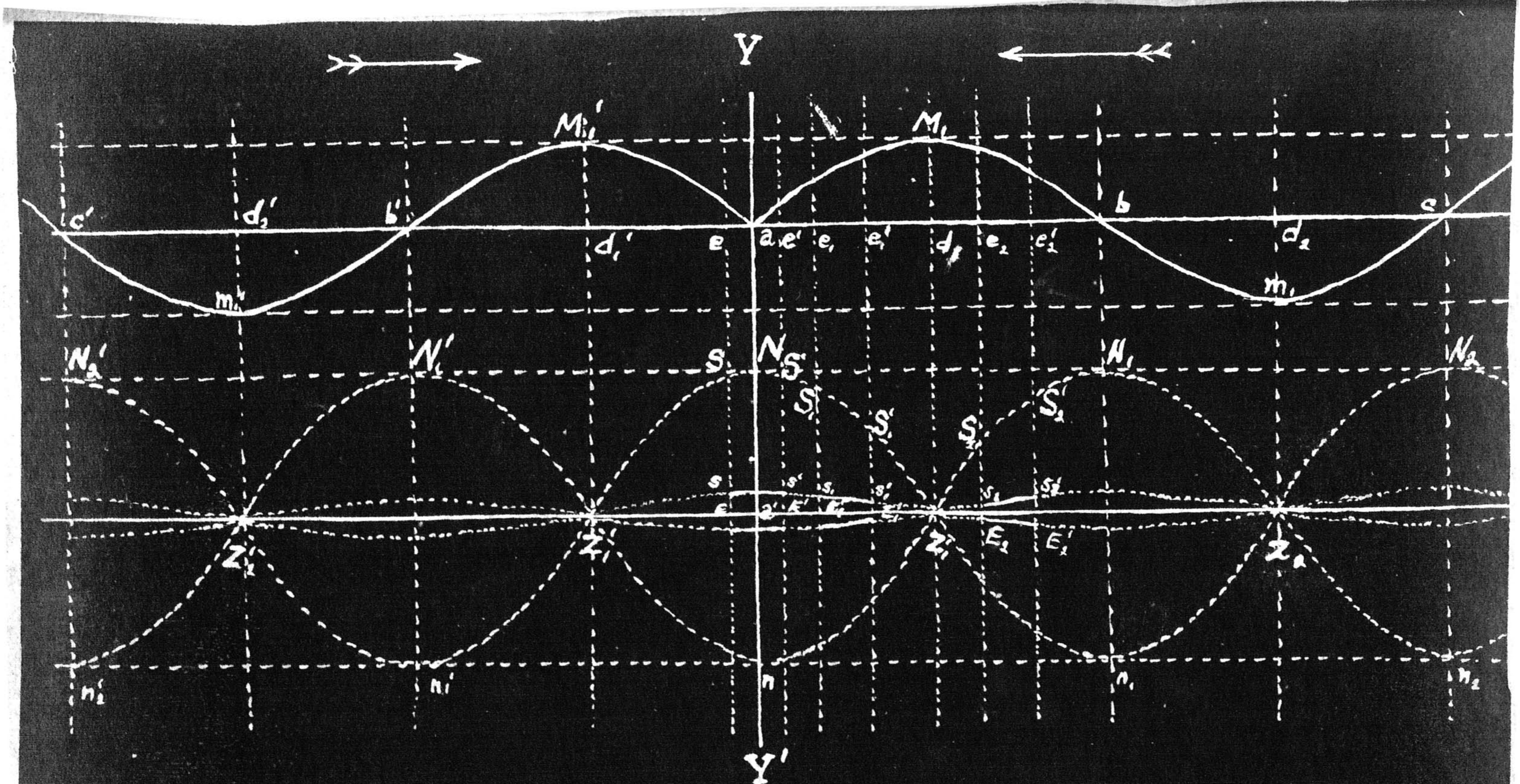


Fig. 4

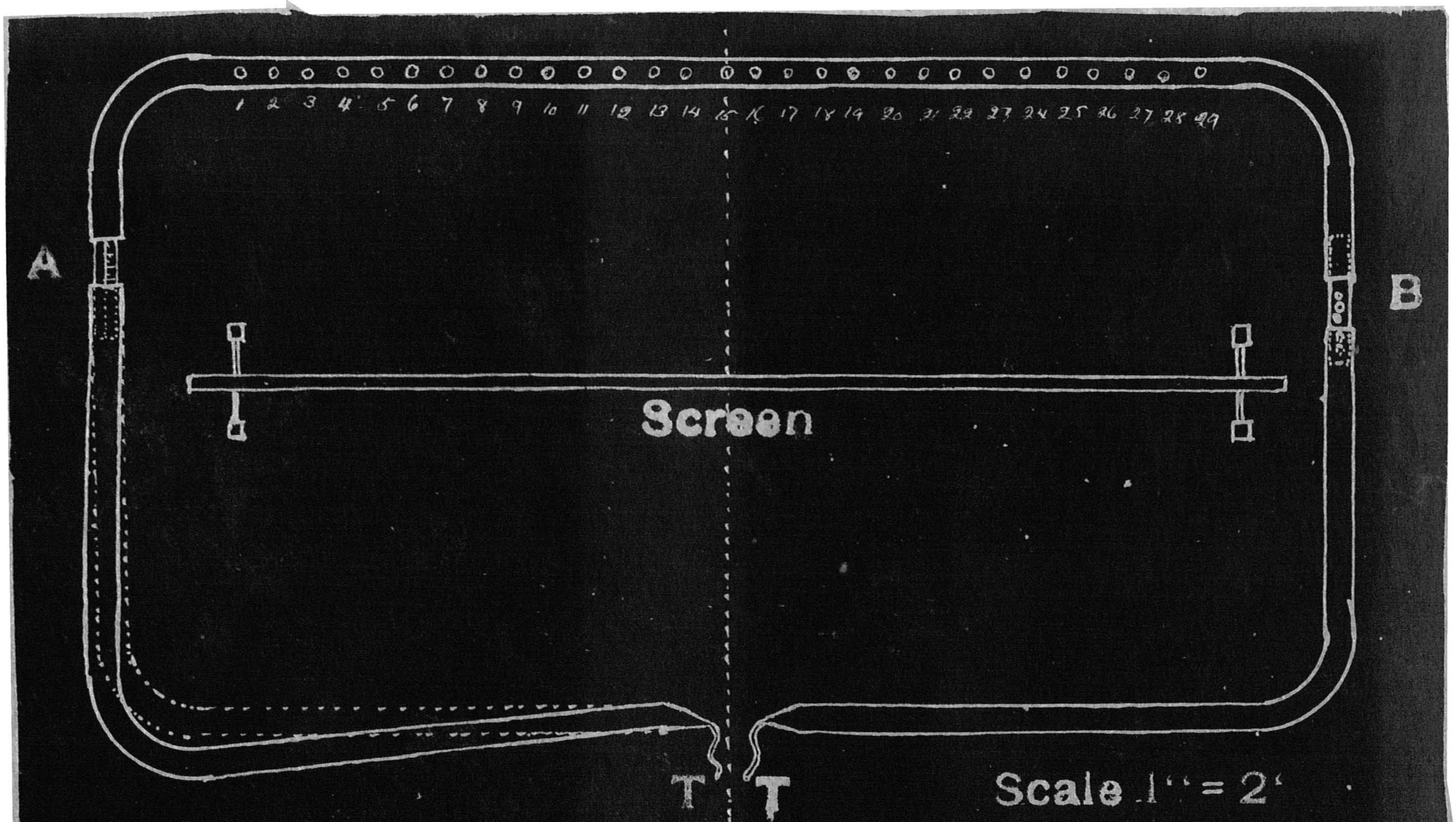
the broken lines $N_2z_2n_1z_1Nz_1'n_1'z_2'N_2'$, and $n_2z_2N_1z_1nz_1'N_1'z_1'n_2'$ whose ordinates represent variation in pressure. At the points z_1, z_2, z_1' and z_2' we have zero variation in pressure and at a' we have a maximum variation in pressure.

Now suppose the ears to be located att the points E and E' equally distant from the point where the two waves meet. There will therefore be zero phase difference. Owing to the damping effect of the head upon the sound waves the "standing"b wave within the head will assume some such form as ss', the ordinates Es and E's' being equal. The two ears will be affected therefore by sounds of equal intensity.

Now suppose the ears to be moved to the points E_1 and E_1' . The standing wave within the head will therefore assume a form like s_1s_1', where the ordinates E_1s_1 and $E_1's_1'$, and E_1S_1 and $E_1'S_1'$ are unequal in the same sense. In this case the auditory apparatus at E_1 is affected by the loudest sound, since the pressure variation in the medium at this point is greater than at the point E_1' . The wave at this point is leading however, since the maximum M_1 of the wave at the left has less distance to travel to affect auditory apparatus E_1', than the corresponding maximum M_1' in the other wave has to travel to affect the other auditory apparatus at E_1. Suppose now that the ears are moved to a second pair of points E_2 and E_2'. The standing wave will assume some such position as s_2s_2', and the ordinates E_2S_2 and E_2s_2, and $E_2'S_2'$ $E_2's_2'$ will be unequal in the same order. The auditoty apparatus at E_2' is now being affected by the louder sound, but the wave at this point is lagging, since the maximum M_1 has passed it less than one quarter of a period before, and the second maximum will follow the maximum M_1' a period of time less than a half period, since the distance $d_1'e_2$ is greater than a half wave length, and less than a whole wave-length less the thickness of the head ($ac - e_2e_2'$).

It thus becomes clear that any interference that may exist in the head leads to difference in intensity which under ordinary conditions cause localization on the side of greater intensity. But these differences of intensity demand localizations just the opposite of those demanded by the theory of localization on the side of the leading wave, and yet Wilson and Myers found localization in the majority of cases that agreed with the phase ratio theory.

It was for the purpose of obtaining more evidence bearing upon the subject of phase ratio, and of attempting to find whether any point had been overlooked in previous investigations, that the experiments to be described were carried out. The apparatus used in this work was built on the same general plan as that of Wilson and Myers. It is shown in the accompanying photographs and in the diagram in Fig. 5. The tubing was made of ordinary coarse wrapping paper, by winding it, while wet with paste, apirally around a long cylindrical form, until twelve or fifteen layers were wound on, the whole tube being slipped off when dry. The tubing thus made was about three inches in diameter, and



1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29
A
B
Screen
T T
Scale 1" = 2'

Fig. 5

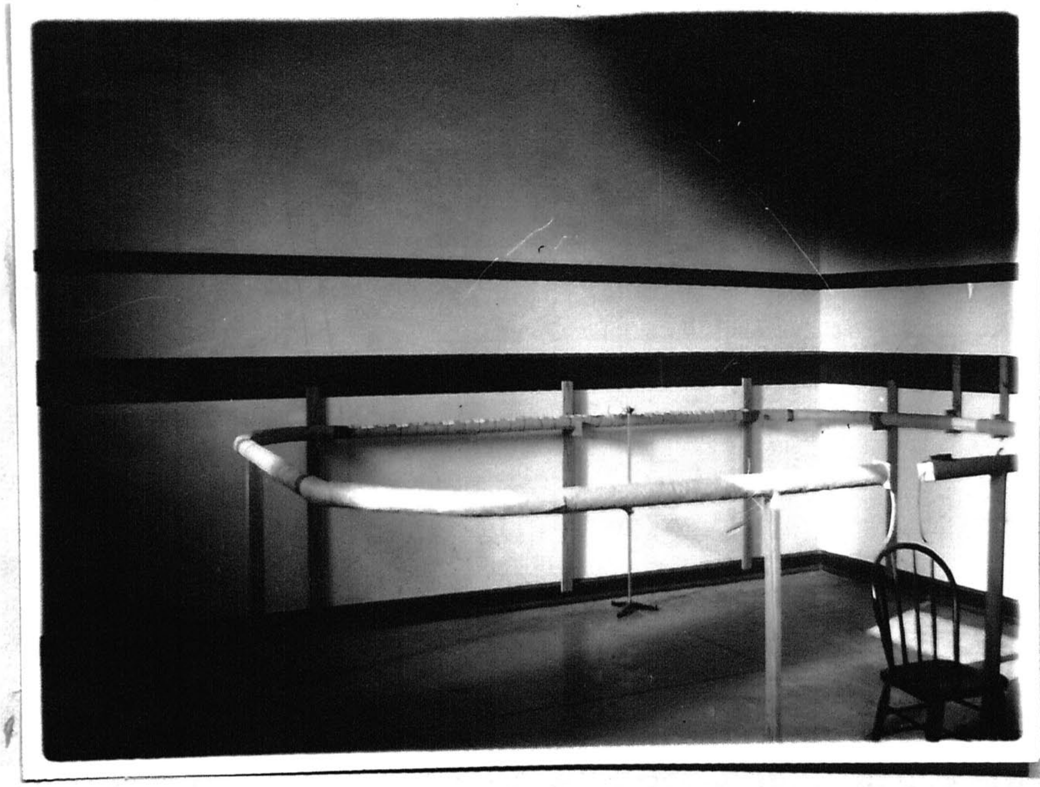


Fig. 6 a

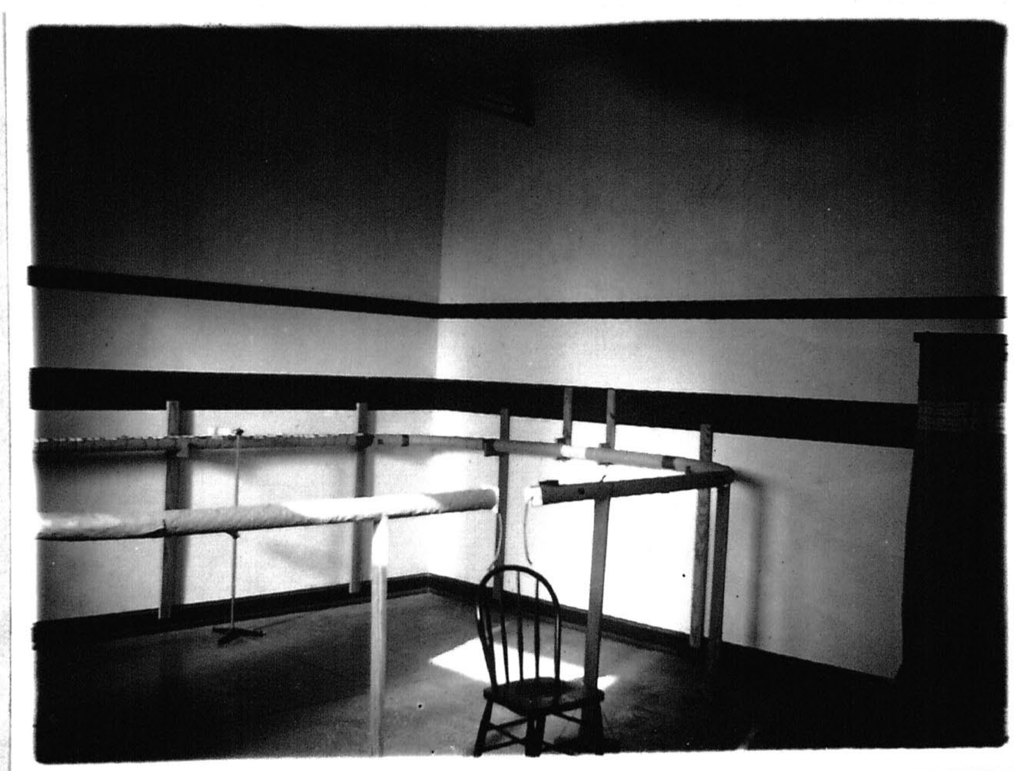


Fig. 6 b

comparatively free from resonance for the high partial tones. Instead of a long sliding section of tube for varying the phase relations, the tubing of one side of the rectangle was perforated at intervals of four inches by holes about two inches in diameter, which were kept closed by rubber lined covers held on by heavy rubber bands. The phase relation was varied by giving the sound at different holes. In order to provide for finer variation of the phase relation, than was afforded by these holes, a short telescoping section capable of eight inches adjustment was introduced into one section of the tube, as shown at A in Fig. 5. At B is shown a slide to provide for variable leakage of sound, and a consequent variation of the intensity of sound traveling this path. This slide was not used in the experiments to any great extent owing to the great uncertainty of measuring changes in intensity due to its use. The tubes terminated in small soft rubber tubes T,T, which were inserted in the subject's ears and held in place by large felt pads. A large screen not shown in the photographs, but represented in the diagram, was used to shut off the view of the subject in the direction of the operator, and also served to diminish the noises that the latter made while manipulating the apparatus.

The small amount by which the sound was damped in passing through the tubes is shown by the fact that a pitch of 24 vibrations, which could not be heard when the fork was more than about one foot from the head in the open air, could be plainly heard through the tubes.

The pitches for which systematice results were taken in this series of expeiments were 32, 64, 100, 200 and 400, although most of the work was done with the pitch of 200 vibrations, since it was considered near enough to the value 128 to afford a practical test of the theory of Rayleigh. Also, what was of more practical importance with this particular form of apparatus was the fact that for pitches of less than 200 vibrations the wave-lengths were too great to secure recurrent localizations.

All of the results take have been represented in the curves given in Figs. 7 to 20. The methods of translating localizations into ordinates of a curve depended upon the subjects. One subject, R, gave his localizations directly in terms of angles of displacement to the right or left. Observer D gave his localizations largely in terms of apparent distances in feet of sounds from the ear. These localizations were transformed into angles by the aid of an auxiliary diagram. The third observer B gave his localizations in terms of distances and positions between the right or left ear and the median plane, within the head. Also, in a large number of cases relative judgements were given, the subject stating that a sound seemed further out to the right or left than the previous sound, etc. These localizations were easy to plot.

In the figures the broken sine curve represents the theoretical variations in localization, which should be given for the corresponding phase relation represented by the abscissae. The abscissae to the right of the center represent the displacement of the sound to the right of the center of the perforated section of tube, and abscissae to the left of the center represent corresponding left displacements. The observer always sat so that his right corresponded to the operators right when the latter faced the perforated tube. Localizations to the right are plotted above the line and localizations to the left, below. The numbers at the different point of the solid curve representing the variation in localization, refer to the order in the series in which the judgements were made.

Fig. 7 shows a very close agreement between the theoretical and actual curves. At the point 7 a shift in localization was noticed, and it should be noted that this shift was in a direction from that demanded by the intensity criterion toward that demanded by the phase difference criterion.

Fig. 8 shows bends and tendencies of the localization curve that correspond to changes in direction of the theoretical curve, even if the curve does not actually cross the line of median localization ordinates. The irregularity in form of this curve may aldo be due to the great difficulty experienced in making a consistent transformation of the subjects introspections into ordinates.

Fig. 9 shows a curve following the theoretical curve quite closely, even at the extreme ends, but many judgements in disagreement with the theory are also to be observed. Many

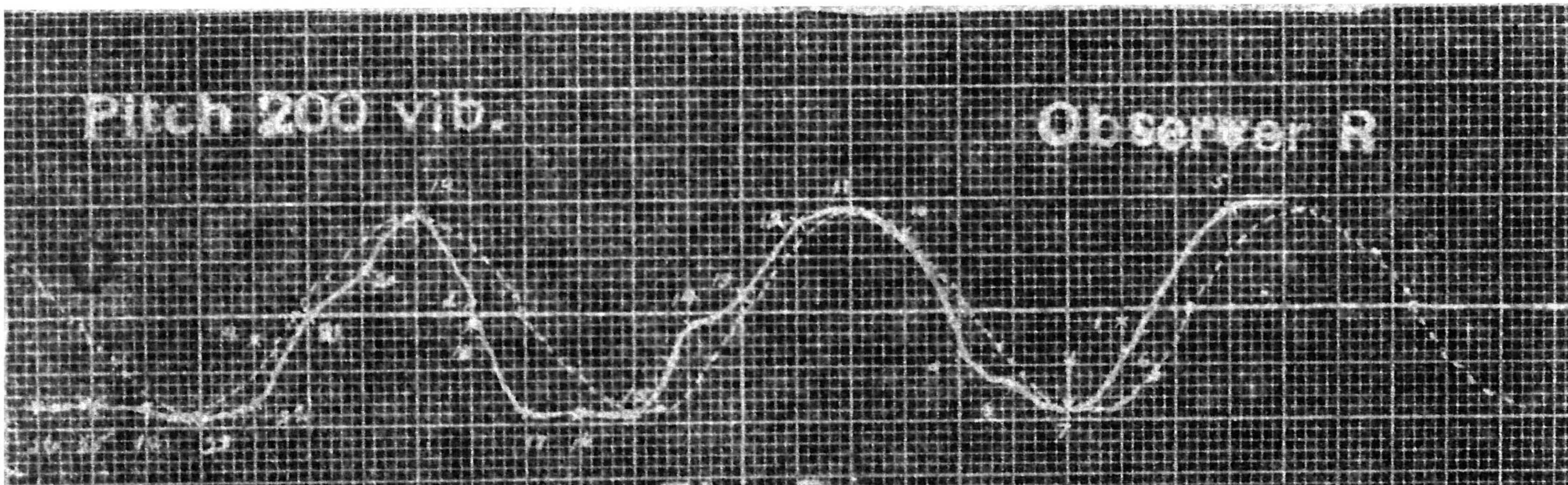


Fig. 7

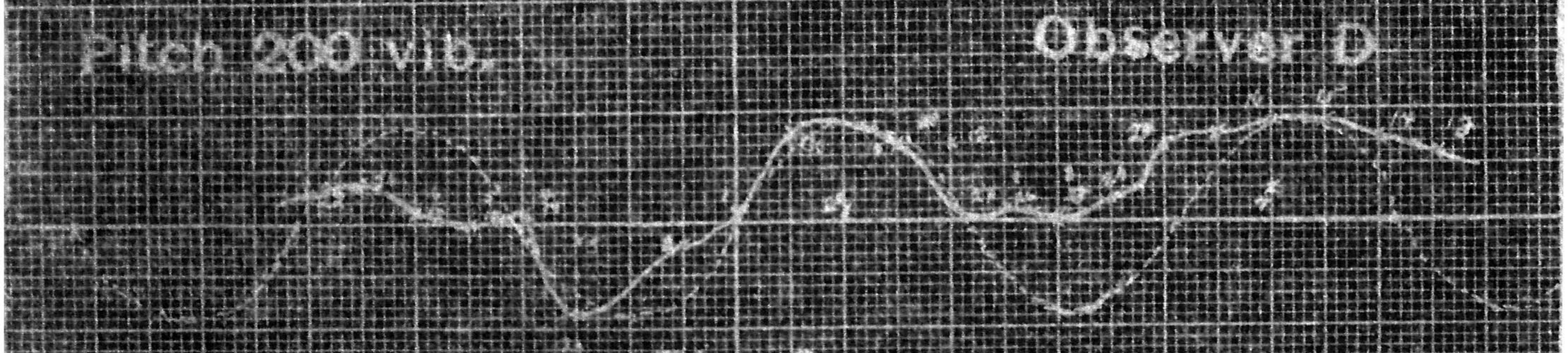


Fig. 8

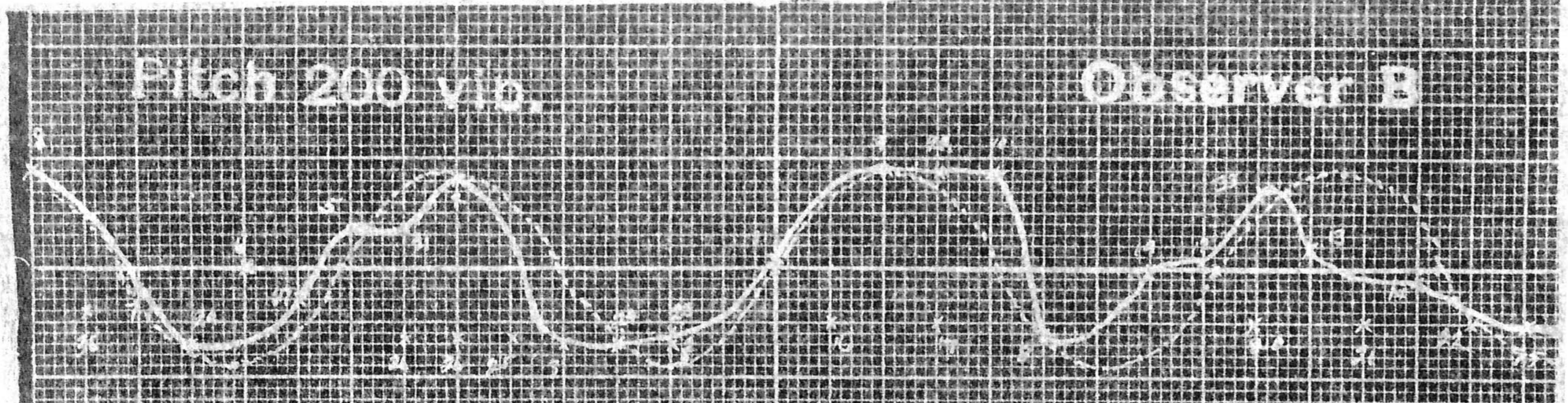


Fig. 9

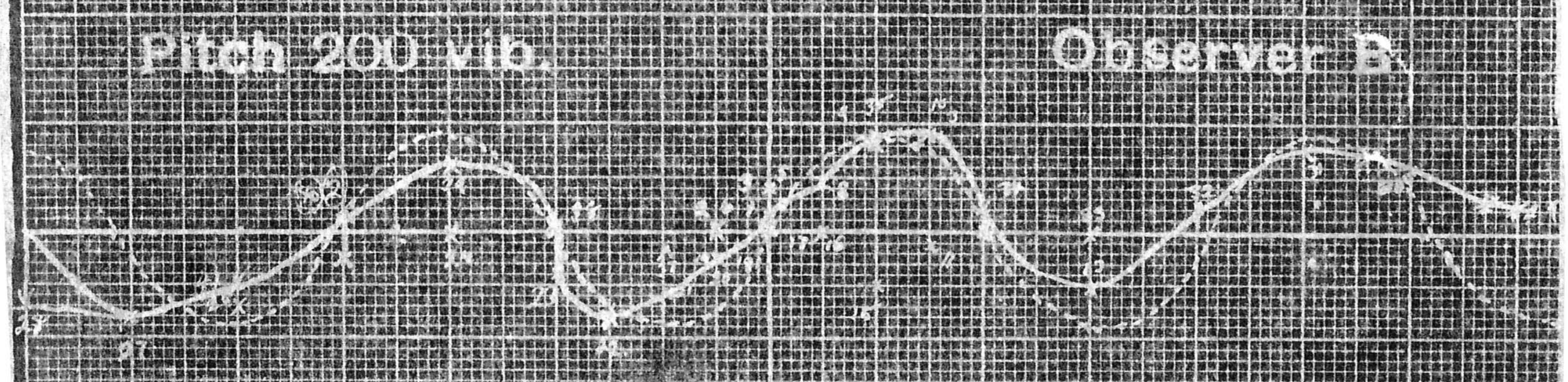


Fig. 10

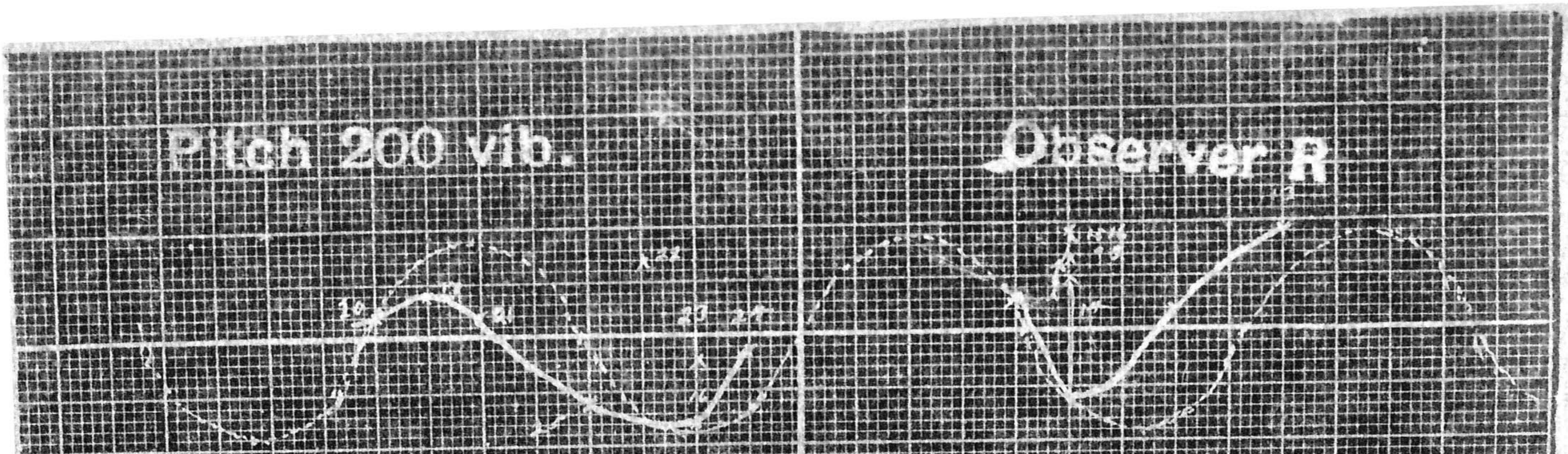


Fig. 11

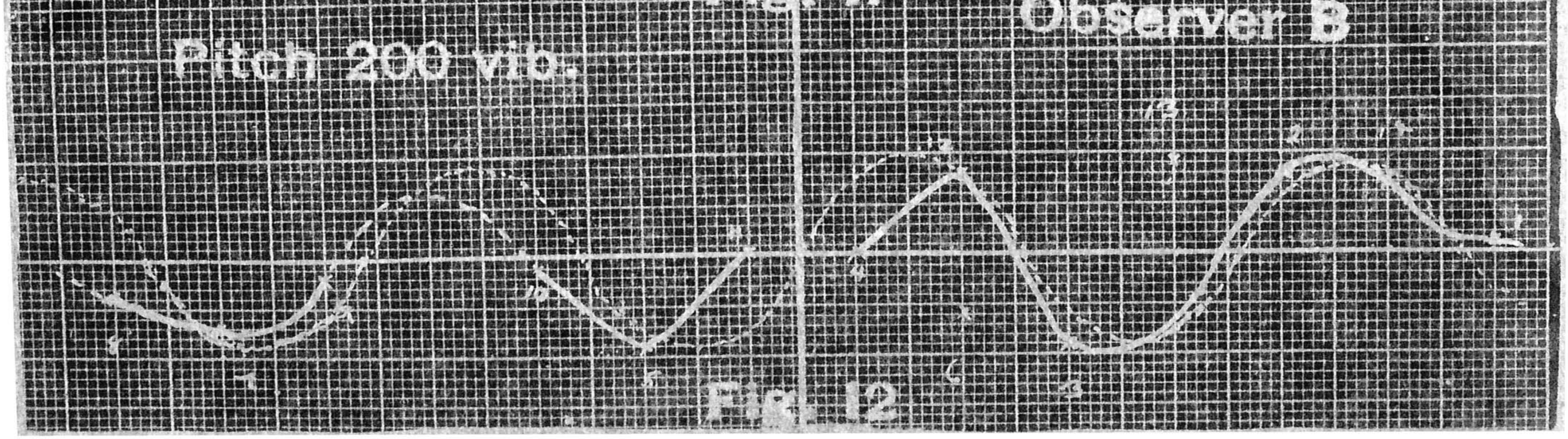


Fig. 12

of these are to be accounted for by the inertia of judgement which was noticeable in this subject throughout all the experiments.

Fig. 10 shows another curve by the same subject, of practically the same nature as Fig. 9, but with more inconsistent judgements, most of which are to be explained as before. One shifting localization is shown at 40, the direction of which is, as in the above mentioned case, away from localization on a binaural intensity ratio basis toward localization on a binaural phase ratio basis.

Fig. 11 shows a curve which is not complete, but closely in agreement with the theoretical curve as far as it goes. A very noticeable shift in localization occurs at 14, of exactly the same nature as those described before. Also several unexplainable, inconsistent judgements, were made at other times on this same abscissa. Although no investigation of the matter was made it is probable that at this point resonance of the tubing disturbed the localization by unknown reinforcements. It might be remarked that Wilson and Myers had a number of similar cases of inconsistent localization which they found to be due to resonance effects. No shifting affects are mentioned by them.

Fig. 12 gives another incomplete curve agreeing closely with the theoretical curve. The anomalous judgement 13 may be explained as due to the inertia of judgement following 12.

Fig. 13 represents a series that it very instructive

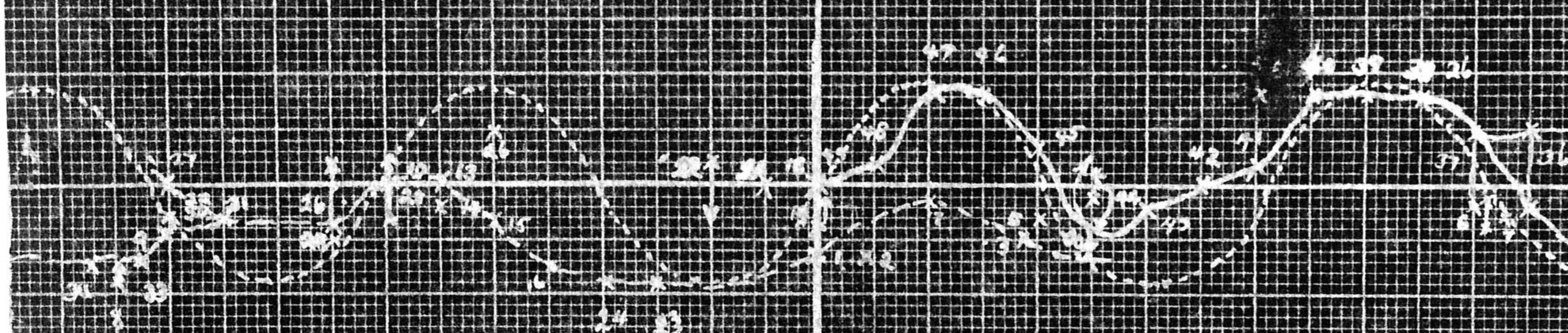


Fig. 13

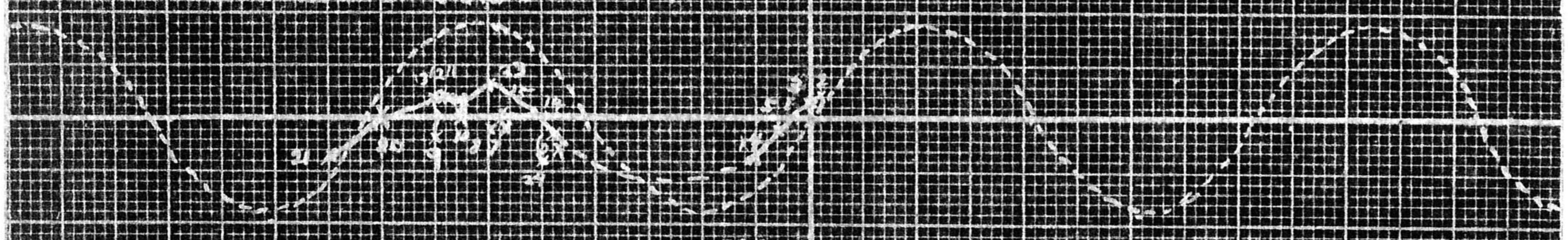


Fig. 14

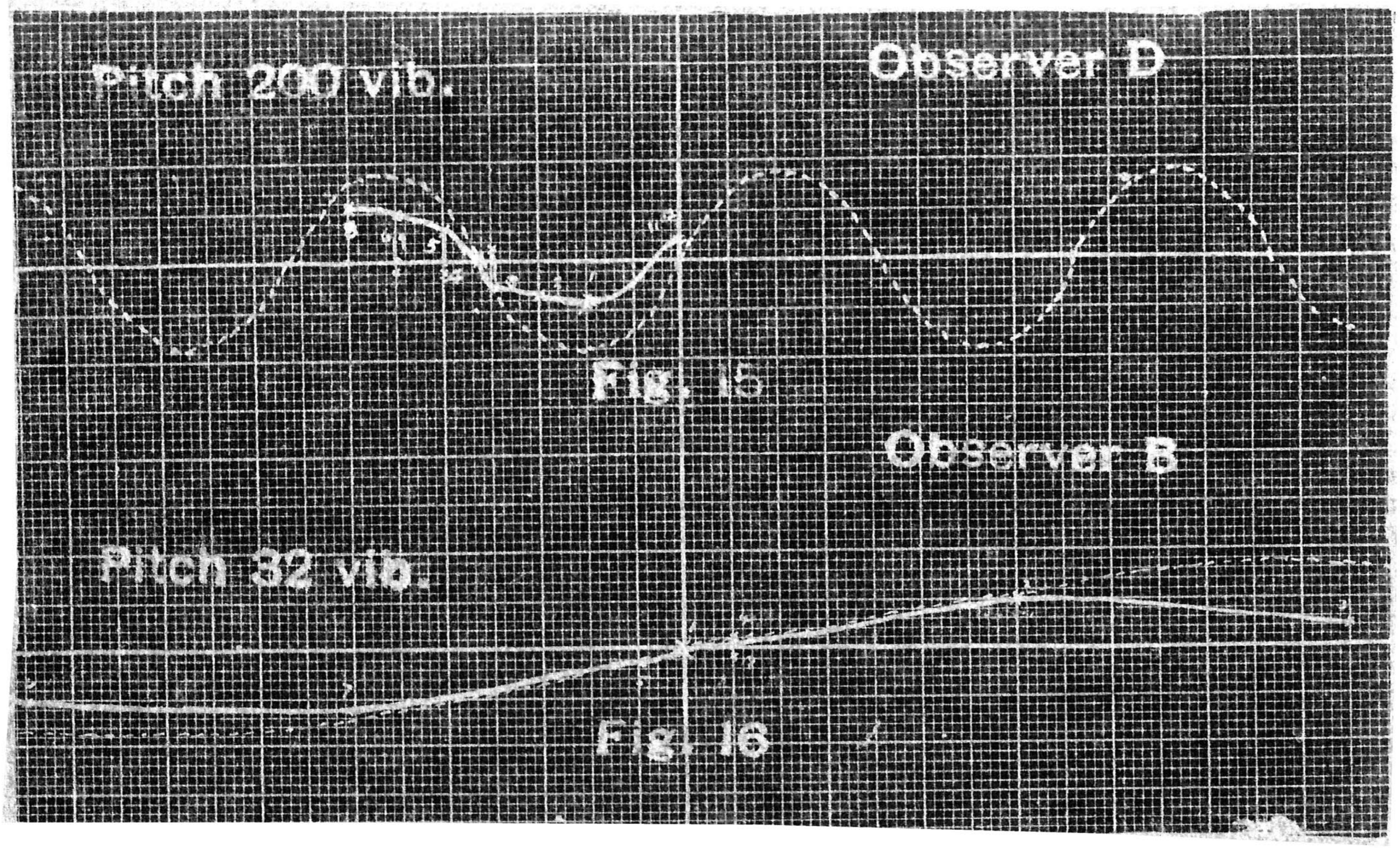
because of its shifting and apparently inconsistent localizations. The series was begun without preliminary adjustment of the position of the rubber tubes leading into the ears, to insure perfect median localizations when the phase difference was zero, and it will be seen that at the first trial, with zero phase difference, the localization was considerably to the left. Evidently there was an intensity difference due to inequality of adjustment of the ear pieces, having the effect of an inequality of sensitivity of the two ears. The broken curve or more irregular character in the left three fourths of the figure is built for the most part upon the results of the first half of the series as may be seen from the numbers along its course. It will be seen that it corresponds in changes of direction fairly well to the theoretical curve, but that it is uniformly displaced downward, or in other terms every localization is displaced to the left because of the constant difference due to the adjustment of the apparatus. The full curve in the left half of the figure is fairly consistent with the theoretical curve, but without any uniform displacements, and it will be seen that this curve is due to the judgements of the last half of the series, taken after the auditory apparatus had become adapted to the initial superimposed intensity difference. The reason for this adaptation is hard to find if we exclude the hypothesis of direct appreciation of phase difference by the auditory apparatus. For in this experiment the subject has no criteria for knowing how correct his judgements are, and any variation in intensity due to inter-ference, etc., would besuperimposed upon the original inequality of sensitivity of th ears,(whether this be natural or artificial) without any tendency to cause adaptation here, for the simple reason that there is no difference in the character of the criteria from these two sources. Adaptation points to comparisom of criteria of different character, and in order to find criteria in this experiment differing in character we must admit the direct appreciation of phase difference by the auditory apparatus.

Shifting localizations are to be seen in trials 8, 10 12, (center), 20, 22, and 44, and all in a direction toward localization by phase difference criteria.

Another peculiarity of this series was the tendency for the sounds to break up into double tones, one in each ear, distinct, and separate. The most noticeable case in the figure is at 36 where it will be seen that one tone corresponded to localization by phase difference, and the other corresponded to localization according to intensity difference. Other cases of the same kind occured in trials 11,13,14,15, 18,19 and 20though not all are shown in the figure

Figs. 14 and 15 represent incomplete series that have no additional significance. In both series the double tones and shifting localizations were observed.

Fig. 16 shows the results obtained with a pitch of 32 vibrations. Owing to the extremely great wavelength


Pitch 200 vib.
Observer D
Fig. 15
Observer B
Pitch 32 vib.
Fig. 16

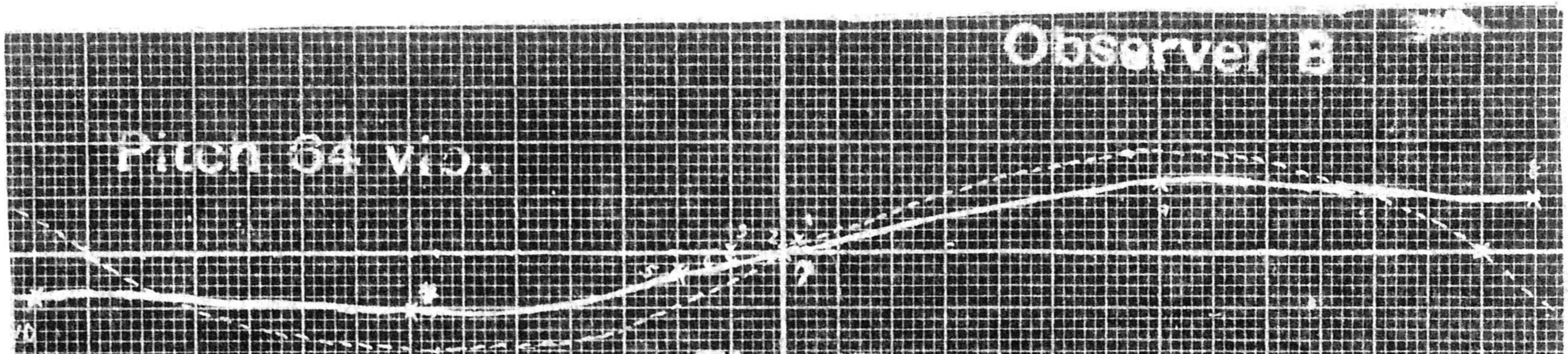


Fig. 17

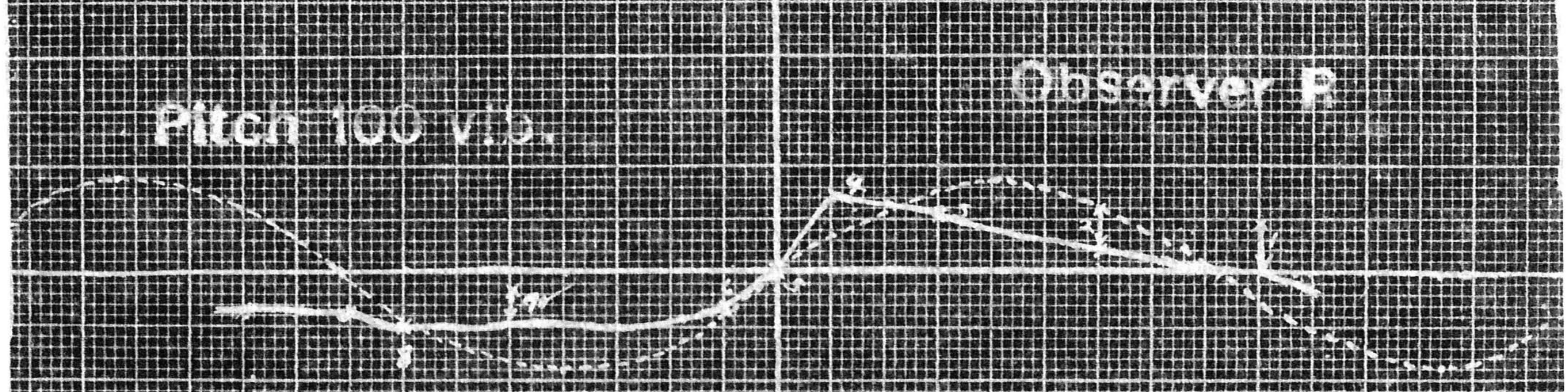


Fig. 18

(about 34 feet) it was impossible to get cyclic localizations but the greater distance to the left of judggment 7 over 6 and of 2 to the right over 3, shows the agreement of the tendency of the curve with the theorrtical curve.

Fig. 17, representing the localizations with a pitch of 64 vibrations, shows exactly the same characteristics as Fig. 16.

Likewise Fig. 18 shows the same characteristics from the use of a pitch of 100 vibrations, with the additional shifting of localization of 1, 2 and 7.

Fig. 19 shows almost perfect results with the use of a pitch of 400m vibrations except that there is a constantly increasing displacement of the judgements toward the right, due probably to a combination of the damping effect of the tubing, and the passage of part of the sound through the open air to the subjects ears. This effect was noticeable with this pitch only. If we were to rotate the coordinate axes about the origin as a center through a small angle in the counter clockwise direction the axis to the right would pass through a position where the localization curve would be almost perfectly symmetrical with respect to it.

Fig.20 shows the results obtained with a pitch of 200 vibrations when the phase difference was varied by very small stages (about $5\frac{1}{2}^{\circ}$). The main point of the series is that it shows that a very slight change in phase difference such as 5° or 6° produces a change in localization usually in the proper direction. Since for 200mvibrations the maximum phase d

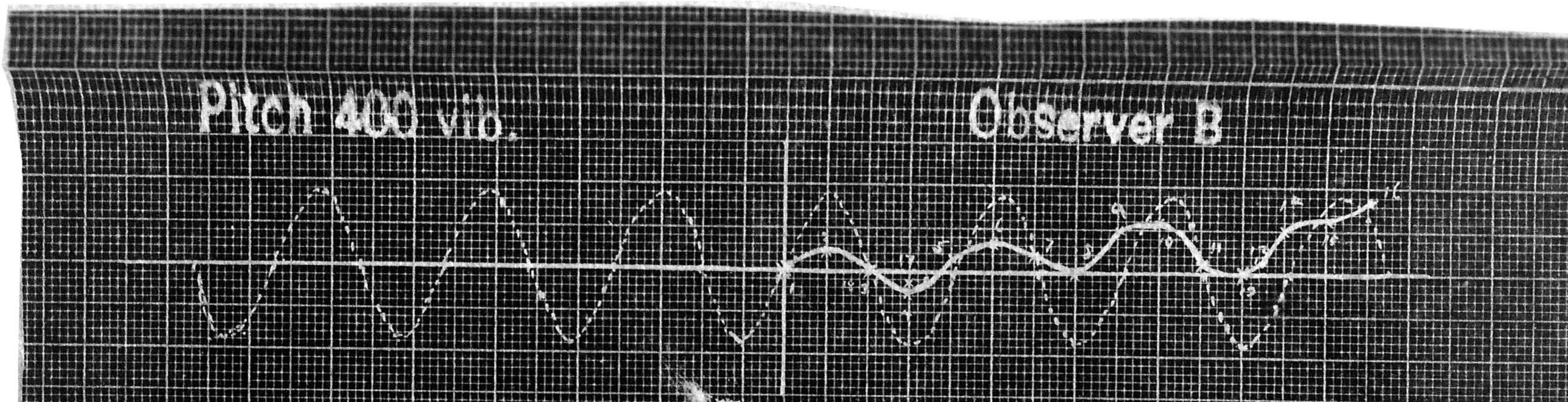


Fig. 19

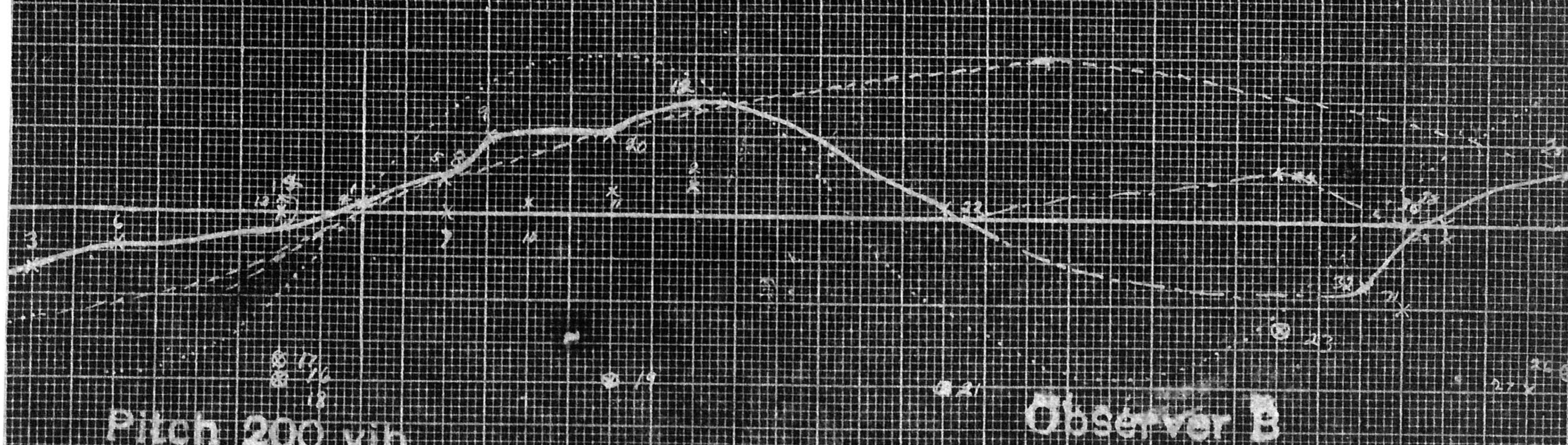


Fig. 20

difference under normal conditions is about 33°, which should cause a total left or right localization, 6° change in phase would correspond to a shift of the source of sound under normal conditions through about one fifth of a quadrant, or about 14°. That this is not inconsistent with the facts concerning just noticeable angular displacements is obvious.

The judgements in Fig. 20 numbered 16, 17, 18, 19, 21, 23 and 26 are due to a slight opening of the leakage slide B as shown in Fig. 5, and have no particular significance except to show that an almost infinitesimal opening of the slide and a consequent small change in intensity is sufficient to produce a very marked change in localization.

The results obtained from these experiments are seen to verify the results obtained by Wilson and Myers, and to verify these results over a range of pitches from 32 to 400 vibrations or over practically the total range of audible sound in which Lord Rayleigh supposed phase differences operative, and over considerable more than he supposed to require criteria of phase differences for localization.

Moreover it has been shown that any interference in the head which thus far ha been tacetly assumed does not produce as greater intensity on the side of the head receiving the leading wave, as Wilson and Myers supposed, but that exactly the opposite state of affairs exists. The probabilities are great that the assumption of transmission of sound through the head would be hard to justify for normal conditions, although there undoubtedly is some when any part of the vibrating body or accessory apparatus touches the head. Notwithstanding the statements of many works on physiological psychology that there is transmission through the head to a "surprising" degree, we have the results of experiments upon persons in whom the auditory apparatus one side of the head was know to be totally destroyed, that when the good ear is carefully plugged nothing can be heard of a sound of ordinary intensity made near the opposite side of the head. Thus is appears that any transmission that may exist is very slight , and that the consequent interfernee is so slight as to be practically negligible.

In any case we arrive at the conclusion that the localization in the experiments carried out under artificial conditions depends upon direct appreciation oft the phase difference by the auditory apparatus, or else that it depends upon the action of the very small amount of interference present in a manner opposite to the way in which intensity differences ordinarily work. This latter absurd supposition is excluded by the fact that the slightest controllable intensity differences in thes experiments, both in conjunction with phase diffeneces and not,acted in the ordinary way as shown in Fig. 30.

This leaves as the conclusion to be drawn that phase differences are directly appreciated by the auditory apparatus. How, is another question, one which has stood in the way of other investigators of this problem, and influenced them to draw opposite conclusions, on account of the difficulty of assuming separate nerve impulses for each sound wave. If we do assume this however, we find that phase difference produces an ultimate result in the auditory center of a rhythm of impulses, in which the period of time following the leading impulse and preseding the lagging impulse is shorter than that following the lagging impulse. This condition may result in a periodic fatigue of the auditory center, so that the leading impulse produces a greater effect, because it comes after a period of recuperation. If such a fatigue effect is present it is seen to account for the median localization under conditions of both 0° and 180° phase difference. the impulses from the two stimuli coming simultaneously in the former case, and alternately, equally distant apart, in the latter case.

In any case the conditions require only that the first impulse of each pair be identified with the auditory apparatus of the proper side.

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